EFFICIENT AND FAST GAUSSIAN BEAM-TRACKING APPROACH FOR INDOOR-PROPAGATION MODELING

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ABSTRACT: *A Gaussian beam-tracking technique is proposed for physical indoor-propagation modeling. Its efficiency stems from the collective treatment of rays, which is realized by using Gaussian beams to propagate fields. The formulation of this method is outlined, the computation-time efficiency is discussed, and the simulation results are compared to those obtained using a commercial ray-tracing software (XSiradif).*

Key words: *indoor radio propagation; Gaussian beam tracking; multipath channel; propagation modeling*

1. INTRODUCTION

The need for fast and accurate tools to evaluate radio propagation in buildings is increasing, together with the evolution of mobile services towards wireless broadband access; these services are planned to be used intensively inside buildings. Ray-tracing methods are the most popular tools for site-specific prediction of field coverage and delay spreads [1– 6]. In ray-launching methods, a large number of rays with a given angular separation between neighboring rays are launched from the transmitter. After computing all transformed (transmitted, reflected, and diffracted) contributing-ray paths, a reception test (generally based on the reception sphere concept) [7–9] is performed for each observation point. The brute-force image method does not require reception tests and provides more accurate results. Nevertheless, this method has been applied only to simple structures because the calculation of image rays is particularly time-consuming for complex environments. There are also several works that use image methods in complex structures together with algorithms that firstly identify all visible surfaces [10].

In indoor environments, fully 3D implementation of these methods is required in order to achieve sufficient accuracy. The complexity of the environment complicates the determination of the paths. Various techniques have been proposed to reduce the number of rays to trace, among which the combined Monte Carlo/ray-tracing method [11, 12], the mixed “ray-launching/tracing” method [13], and the “tube ray-launching” technique [14].

In this paper, we propose a Gaussian beam-tracking (GBT) algorithm for physical indoor-propagation modeling as an alternative to ray-based methods. Using Gaussian beams instead of rays provides an inherent limitation of the number of rays to trace, due to the fact that beam equations are valid at any point in a given environment, and not only along a line of zero thickness, as is the case with rays.

The accuracy of this method has already been demonstrated in a demanding multipath context (metallic waveguide), where the number of successive reflections encountered by a beam was more than 250 [15].

2. FORMULATION OF THE METHOD

The starting point of the method is the expansion of the source antenna-field spectrum into a set of Gaussian windows $\widetilde{w}(k_x,\ k_y)$ generated by translation in spatial and spectral domains to form a Gabor frame [15–17]. For example, the expression of the projection of the source antenna-field spectrum on the Ox axis is given by:

$$\widetilde{E}_x(k_x,\ k_y) = \sum_{m,n,p,q\in\mathbb{Z}} A_{mnpq}\,\widetilde{w}(k_x - n\kappa_x,\ k_y - q\kappa_y)e^{j(ml_x x)}e^{j(pl_y y)} \tag{1}$$

where A_{mnpq} are the coefficients of the source-spectrum decomposition on the Gabor frame. The Gabor decomposition indices m, p (respectively, n, q) correspond to translations of the x and y spatial variables (of the respective k_x and k_y spectral variables). l_α and κ_α are, respectively, the spatial and spectral shifts along the α and k_α coordinates (α stands for x or y).

$\widetilde{w}(k_x,\ k_y)$ is a Gaussian window defined by

$$\widetilde{w}(k_x,\ k_y) = \left(\sqrt{2}L_x\right)^{1/2}\left(\sqrt{2}L_y\right)^{1/2} e^{-\pi(k_x/\Omega_x)^2}e^{-\pi(k_y/\Omega_y)^2}, \tag{2}$$

with L_x, L_y (respectively, Ω_x, Ω_y) its widths along x and y (respectively, k_x and k_y).

These windows radiate in the form of Gaussian beams, whose propagation can be expressed, via paraxial approximation, by simple analytical formulas. L_x and L_y are chosen sufficiently large for the approximation to be valid. The field radiated at an observation point $M(x, y, z)$ is thus obtained by superposition of the Gaussian-beam fields:

$$E(M) = \sum_{m,n,p,q\in\mathbb{Z}} A_{mnpq}e^{j(mnl_x\kappa_x + pql_y\kappa_y)}B(M)\mathbf{u}_{nq}. \tag{3}$$

B_{mnpq} are the Gaussian beams radiated by the windows, which constitute the frame, and $\mathbf{u}_{nq}$ denotes their E-field direction [15]. The paraxial expression of these beams can be put in the following form:

$$B_{mnpq}(M) = \sqrt{\frac{2}{L_xL_y}}\left(\frac{\det(\mathbf{Z}(z_i))}{\det(\mathbf{Z}(0))}\right)^{1/2} e^{ikz_i}e(jk/2)\xi_i\mathbf{Z}(z_i)\xi_i^T \tag{4}$$

with $\mathbf{Z}(z_i) = z_iI_d - jCM_LC^T$, where $I_d = \begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}$, $M_L = \begin{pmatrix}\frac{L_x^2}{\lambda} & 0\\ 0 & \frac{L_y^2}{\lambda}\end{pmatrix}$ and C is a projection matrix of the global coordinate system with regard to that associated with the incident-beam axis [15]. In the above relation, $\xi_i = (x_i, y_i)$ and z_i are the coordinates of the observation point $M(x_i, y_i, z_i)$ in a system associated with the incident beam axis, and superscript T denotes transposition. When a Gaussian beam impinges on a plane interface, the reflected and transmitted fields can be expressed in the form of Gaussian beams. The directions of the transformed beams axes are obtained by application of Snell's law. The Gaussian-beam expression for the reflected fields is that of an "image" beam, originating in an equivalent "image" source window [15]; its origin is symmetric to the incident-beam origin with respect to the reflection plane. Multiple reflections and transmissions can be treated iteratively for each frame beam, and the total multipath field in a given environment results very easily by superposition.

3. BEAM TRACKING PROCEDURE

The proposed GBT algorithm is divided into two parts. The first one performs the geometrical tracking of the beam axes within the environment, and the calculation of transformed (by reflection and/or transmission) beams parameters; these parameters are stored into files.
The second one carries out the calculation of beam fields, by using the previously stored parameters to compute the analytical expressions of the Gaussian beams; the total electromagnetic field is obtained by summing up these fields, weighted by the Gabor frame coefficients of the source decomposition. A number of initial data must be provided to the program which performs this algorithm:

- a file describing the propagation environment in the form of rooms;
- a file containing the coefficients of the source decomposition for the chosen Gabor frame whose parameters (L_α, l_α, and κ_α, for $\alpha = x, y$) must also be provided to the program;
- R_{max}, the maximum number of interactions which will be considered per beam (this parameter is a stop test during a beam tracking);
- the limits of truncation (M, P, N, and Q) in the Gabor-frame summations, which define the number of source beams to be launched and tracked (there is a trade-off between the accuracy of the source-field reconstruction and the computation time).

The program starts by launching a source beam in a direction given by m, n, p, and q. At the point of interaction with a wall, the incident beam gives rise both to a transmitted beam and a reflected one. A test is carried out on these beams to determine whether or not they leave the simulation environment. If not, their direction and origin are saved, as well as the point of interaction, the wall of interaction, and the room where the transformed beam will propagate.
The transformed beams are used as source beams for the next reflection and transmission. This process continues until the considered transformed beam leaves the simulated environment. If the number of interactions reaches R_{max} before leaving the environment, the beam is discarded (its contribution to the total electromagnetic-field amplitude is considered to be negligible). A new source beam is then launched and tracked. The number of operations needed to compute a coverage map is then proportional to

$$N_{beam}\alpha^{R_{\max}}\left(n_{beam-path} + \frac{N_{pts}}{N_{rooms}} n_{beam-field}\right), \tag{5}$$

where N_{beam} stands for the number of source beams, α is a coefficient less than two, which is related to the number of beams generated at interfaces and actually propagating in the environment (for an infinite environment $\alpha = 2$), $n_{beam\text{-}path}$ represents the number of operations needed to calculate the parameters of a given transformed beam, and $n_{beam\text{-}field}$ represents the number of operations needed for the calculation of beam fields at a receiving point. The number of receiving points N_{pts} is divided by the number of rooms N_{rooms} in the simulated environment;

the beam contribution to the total field is calculated only for the room where it propagates. For the same environment, the ray-launching algorithm complexity is a priori proportional to

$$N_{ray}\alpha^{R_{\max}}\left(n_{ray-path}+\frac{N_{pts}}{N_{rooms}}(n_{ray-field}+n_{reception\text{-}test})\right),\qquad (6)$$

where N_{ray} is the number of rays launched from the source and $n_{ray\text{-}path}$, $n_{ray\text{-}field}$, and $n_{reception\text{-}test}$ are the number of operations needed to compute a ray path, respectively, they are used to compute the associated field at a given point and to test out whether the ray contributes to the total field at a specific receiver point. A comparison of Eqs. (5) and (6) illustrates the interesting aspect of GBT: using Gaussian beams instead of rays provides an inherent limitation of the number of rays to trace, due to the fact that beam equations are valid at any point in a given environment, not only along a line of zero thickness, as in the case of rays. Moreover, the obtained coverage is uniform without the need to perform a reception test for each point, in contrast to ray methods.

4. NUMERICAL RESULTS

The GBT algorithm presented above is used for coverage simulations in an indoor environment (a house) at 60 GHz. The dimensions of the house are 10.5 x 9.5 x 2.5 m. The building materials are mainly breeze blocks, plasterboards, and bricks. There are large double-glazing windows and a fireplace in house. Figure 1 shows the power coverage obtained with GBT and a ray-tracing tool (X-Siradif®). The transmitter uses a patch antenna placed in a corner of the main room of the house, at a height of 2.2 m near the ceiling and slightly pointed toward the ground (by 15°). The azimuth angle is 50°, as shown by the white arrow [see Fig. 1(b)]. The receiving antenna (Rx) is a horn placed at a height of 1.2 m. During the simulation, for each reception point, the horn is pointed towards the azimuthal direction, thus allowing the highest received power. More details are given in [3]. As one can observe in Figure 1, the comparison of the power distribution in the environment, obtained with GBT and (X-Siradif®), is very satisfying.

The efficiency of GBT is also due to the number of Gaussian beams needed for the pattern representation of the transmitting antenna.

Figure 2 shows a comparison of the far-field patch-antenna pattern obtained using the beam-launching method with a measured pattern. For the Gabor-frame decomposition, we take $Lx = Ly = 30\lambda$, $l_x = l_y = \sqrt{0.75}\,L_x$, and $\kappa_x = \kappa_y = 2\pi\sqrt{0.75}/l_x$, which yields a truncation limit $N = 30$ in the spectral domain [15]. We take only one frame-source beam origin in the spatial domain ($M = 0$). The total number of source beams to be launched is then equal to 61. The accuracy of the obtained results can be considered sufficient for coverage calculations, and this illustrates the flexibility of the frame-based decompositions: various tradeoffs can be performed between the accuracy and computational efficiency, and they all yield uniform results (with no arbitrary discontinuity).

In ray-launching methods, rays are launched in all spatial directions with a defined angular step (usually 1° in indoor environments). This yields a minimum of 141 rays to be launched (approximately from -70° to 70° in 2D) for a correct radiation pattern representation down to a -30 dB sidelobe level.

5. CONCLUSION

In this paper, an original method for indoor-propagation modeling, based on a Gabor-frame decomposition of the electromagnetic source field and Gaussian-beam tracking, has been presented. The principle of the GBT method has shown its computational efficiency.

The numerical results have illustrated its validity. Comparisons with wideband experimental results should be done in order to completely validate the method.

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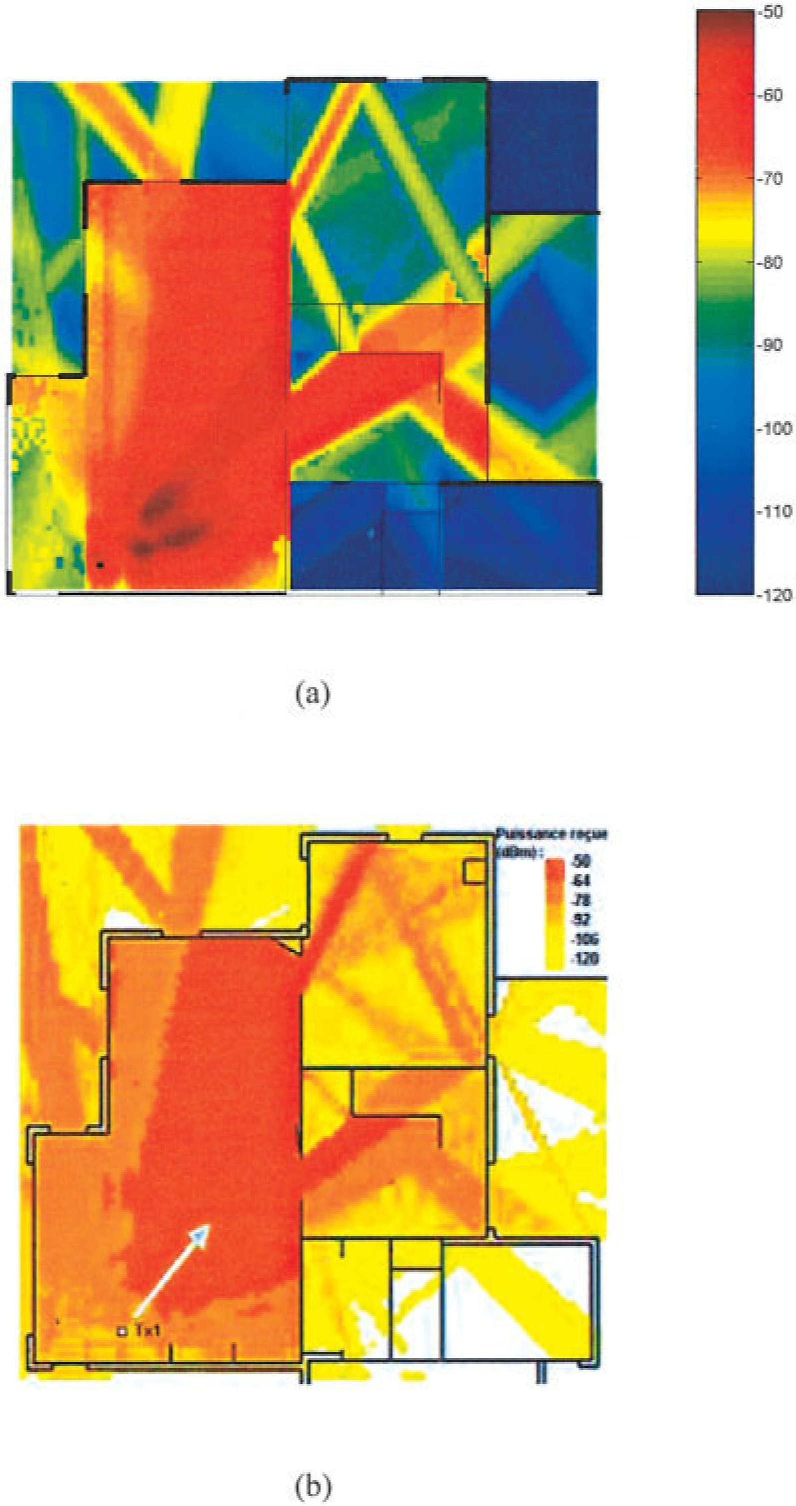

Figure 1 Comparison between GBT and ray tracing: (a) GBT; (b) Xsiradif.

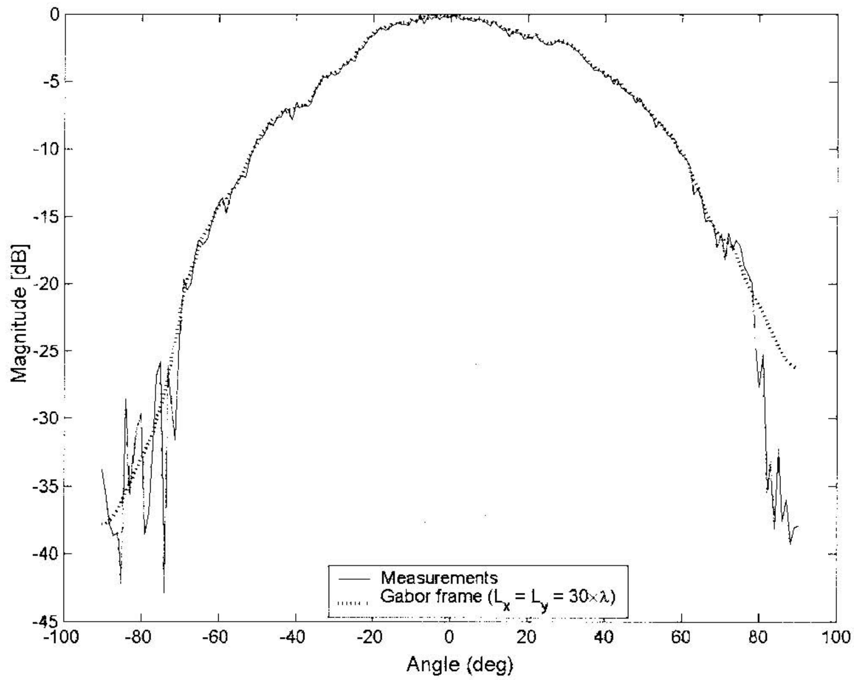

Figure 2 Far-field antenna pattern of a patch antenna, computed by launching only 61 Gaussian beams